

AIR COMMAND AND STAFF COLLEGE

AIR UNIVERSITY

IDEAL DIRECTED-ENERGY SYSTEM TO DEFEAT
SMALL UNMANNED AIRCRAFT SYSTEM SWARMS

by

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Biography

Major David Pina is assigned to the Air Command and Staff College, Air University, Maxwell Air Force Base, Alabama. He is a US Air Force senior pilot, with combat experience in both the MQ-9 Reaper and MQ-1B Predator remotely piloted aircraft spanning Operations ENDURING FREEDOM, NEW DAWN, and UNIFIED PROTECTOR. Prior to pilot training, Major Pina began his career as Logistics Management Specialist for the APY-1/2 radar on the E-3 Airborne Warning and Control System (AWACS) platform and later as Deputy Program Manager for the \$700M digital ALR-69A Radar Warning Receiver program. Operationally, he has served as Flight Commander, 18th Reconnaissance Squadron; Chief of Flight Safety, 556th Test and Evaluation Squadron; and the Assistant Chief of Standardization and Evaluation and Director of Staff, 53d Test and Evaluation Group. Prior to attending Air Command and Staff College, Major Pina served as the Director of Operations, 556th Test and Evaluation Squadron.

Abstract

The proliferation of small unmanned aircraft systems (sUAS), miniaturization of sensor technology, and advancement of UAS swarm logic foretell that swarms of sUAS will threaten US airbases by the 2025 timeframe. Currently fielded base defense systems are not well suited to combat this emerging threat. Current directed energy (DE) developmental systems indicate this class of weapons is the best solution. A review of several continuous wave laser, pulsed high-powered microwave, and electronic warfare/jamming systems indicate the following attributes as ideal for a future directed energy weapon (DEW) system to defeat swarms of sUAS: scalable, layered, fused, modular, and open. In order to ensure DEW systems become a normalized component of the USAF base defense operations, DEW effects should be incorporated into the Joint Munitions Effectiveness Manual, DEW collateral damage considerations should be explored and standing guidance developed, and DEW system employment/command and control concepts of operations should be developed, tested, and evaluated. These recommendations should be acted upon immediately as DEW systems are already being employed to counter individual sUAS and the sUAS swarm threat will soon arrive.

Introduction

It is an otherwise peaceful early summer morning in 2025 at Spangdahlem Air Base, Germany. F-35A Lightning II aircraft assigned to the 480th Fighter Squadron sit quietly on the ramp after returning from Red Flag 25-3 at Nellis Air Force Base, Nevada. These aircraft, as well as their associated aircrew and support personnel, will soon deploy to an undisclosed location in Southwest Asia in support of US Central Command's mission to disrupt and counter violent extremist organizations and their networks.

At 0535 local time, a regional air traffic control facility notifies the 52d Security Forces Squadron base defense operations center personnel that the pilot of a commercial aircraft departing from a nearby airport reported what appeared to be a large group of small unmanned aircraft systems (sUAS) operating outside of airspace where UAS activity is permitted.¹ At 0545 local time, Spangdahlem base defense systems identify a swarm of approximately 300 sUAS approaching from the northeast. Once the swarm threat is in range, these defensive systems attempt to positively identify a potential threat and replace individual UAS navigation commands with alternate commands for the drone to return to its point of origin. In accordance with current standard operating procedures, security forces personnel provide authorization for base defense systems to engage once the approaching swarm meets threat criteria.

Individual UAS targeted by jamming techniques rely on information from non-targeted UAS and continue to commanded geographical reference points before switching to a sensor driven mode. By 0548 local time, the entire swarm transitions to sensor mode with a third of their hyperspectral imaging systems² calibrated toward one of three elements. One hundred of the UAS locate, de-conflict, and target objects highly saturated with various munitions material;

another 100 UAS target petroleum products; and the final 100 UAS target a composite material common to F-35A aircraft recently leaked by an adversary intelligence agency. Some of the drones, constructed partially out of a lightweight, explosive material, explode upon contact with their targets and others within designated proximity.

Expanding applications for UAS in the commercial sector, the proliferation of sUAS in the civilian marketplace, and advancements in semi-autonomous and autonomous technology make this fictional vignette a very likely threat to US Air Force airbases in the 2025 timeframe. This paper follows closely on the heels of 2016 works by Lt Col Leslie Hauck, Lt Col Thomas Palmer, and Dr. John Geis that also examined directed energy (DE) as a potential area for increased US Air Force investment to combat the future UAS threat.³ The Islamic State of Iraq and the Levant's use of sUAS armed with explosives against US and Coalition forces in 2016 highlights the importance of developing adequate countermeasures now.⁴

This paper argues the US Air Force must immediately invest in DE defensive systems to counter the emerging threat swarms of sUAS will soon pose to US airbases. The US Air Force will be unable to fulfill its Title 10 requirements in the face of the UAS swarm threat without a concerted strategic focus of the joint team and the astute application of US taxpayer resources. The potential costs of not being prepared to defeat a drone swarm increase as the number of UAS capable of making up a swarm increases.

This paper will begin by defining the terminology used throughout and then discuss the technological indicators that foretell the sUAS swarm threat to US airbases. Next, it will overview DE techniques available to defeat sUAS and summarize several current (and promising) military and industry DE system development efforts. Finally, the paper will provide attributes of the ideal directed energy weapon (DEW) system to defend against sUAS swarms

and provide recommendations to ensure DE systems become a normalized component of US Air Force base defense concepts of operations (CONOPS).

Terminology

The Federal Aviation Administration (FAA) defines a UAS as “an aircraft that is operated without the possibility of direct human intervention from within or on the aircraft.”⁵ Although the FAA defines these aircraft as UAS, other entities use different terms to identify them. For example, the US Air Force identifies these systems as remotely piloted aircraft (RPA) while their parent organization, the Department of Defense (DoD), refers to them as UAS. Other terminology commonly used to identify these aircraft include unmanned aerial vehicles (UAV) and drones. The term UAS will be used throughout this paper.

The DoD categorizes UAS into Groups according to their maximum takeoff weight, normal operating altitude, and maximum airspeed. See Figure 1 for a description of DoD UAS categorization broken down into Groups 1-5. Updated DoD UAS classification methodology is likely forthcoming since UAS technological advancements enable higher aircraft performance than Figure 1 accounts for by weight. For example, UASUSA’s Tempest aircraft maximum takeoff weight is 17+ pounds (vehicle plus payload) making it a Group 1 UAS.⁶ However, the Tempest has operated at altitudes up to 15,000 feet putting it into the Group 3 category. Since performance capabilities will continue to grow, the focus of this paper are those categorized by the DoD as Group 1 or 2 UAS by weight (55 pounds or less) and these aircraft will collectively be referred to as sUAS.






UAS Groups	Maximum Weight (lbs) (MGTOW)	Normal Operating Altitude (ft)	Speed (kts)	Representative UAS	
Group 1	0 – 20	<1200 AGL	100	Raven (RQ-11), WASP	
Group 2	21 – 55	<3500 AGL	< 250	ScanEagle	
Group 3	< 1320	< FL 180		Shadow (RQ-7B), Tier II / STUAS	
Group 4	>1320		Any Airspeed	Fire Scout (MQ-8B, RQ-8B), Predator (MQ-1A/B), Sky Warrior ERMP (MQ-1C)	
Group 5		Reaper (MQ-9A), Global Hawk (RQ-4), BAMS (RQ-4N)			

Figure 1: DoD UAS Group Descriptions⁷

Threat Discussion

Three indicators necessitate US Air Force preparation for an imminent sUAS swarm threat: 1) the proliferation of sUAS, 2) the miniaturization of sensor technology, and 3) the advancement of UAS swarm logic. The first indicator necessitating US Air Force defenses against sUAS swarms is the proliferation of these systems. According to FAA estimates, the number of hobbyist sUAS in the US will increase from 1.1 million in 2016 to 3.5 million in 2021.⁸ These estimates only account for UAS weighing 55 pounds or less purchased in the US for personal use. The FAA further estimates the number of sUAS conducting commercial

activities in US airspace to increase from 42,000 in 2016 to 420,000 in 2021.⁹ As some say, “business is booming” in the sUAS industry.

The second indicator necessitating defenses against sUAS swarms is the miniaturization of sensor technology. Hyperspectral imaging technology is one example of sensor miniaturization. Headwall Photonics claims to be “the world's foremost integrator of hyperspectral imaging sensors and [UAS] for applications such as precision agriculture, minerals and mining, environmental analysis, military/defense, and pipeline inspection.”¹⁰ Their sensors cover various spectral ranges, from ultraviolet (UV) (250-500 nanometers) to long wave infrared (LWIR) (8,000-12,000 nanometers).¹¹ The small size and weight of Headwall Photonics sensors make them ideal for sUAS applications. For example, Headwall’s Nano-Hyperspec system is only 3 inches x 3 inches x 5.1 inches and weighs just 1.32 pounds.¹² The Nano-Hyperspec system also includes 480 GB of on-board storage capacity (approximately 130 minutes of processed hyperspectral imagery at 100 frames per second) and could be integrated with light detection and ranging (LiDAR) capabilities.¹³ Headwall Photonics has integrated the Nano-Hyperspec system with DJI’s Matrice 600 hexacopter sUAS.¹⁴ Available on Amazon.com for \$4,999 today,¹⁵ the Matrice 600 can hover at 32 feet above sea level for 40 minutes with no payload or capture video from that altitude for up to 18 minutes with a 12-pound payload.¹⁶ The Matrice 600 can achieve speeds up to 59 feet per second and altitudes up to 8,200 feet above sea level.¹⁷ Hyperspectral imaging systems are but one example of miniaturized sensor technology that could enhance the lethality of future sUAS swarms.



Figure 2: Headwall Photonics Nano-Hyperspec Integrated with DJI Matrice 600 sUAS¹⁸

The third indicator necessitating defenses against sUAS swarms is the advancement of UAS swarm logic. The Merriam-Webster Dictionary defines a swarm as “a large number of animate or inanimate things massed together and usually in motion.”¹⁹ Unlike bees that developed swarming behaviors over time, human developed software provides swarming logic to UAS. The Intel Corporation is the face of swarm logic advancement in the commercial marketplace and set multiple records in recent years. From 2015 to 2017, Intel increased the quantity of sUAS in their light shows conducted around the world from 100 to 500.²⁰ One of Intel’s more recent sUAS swarms demonstrations occurred during the 2017 National Football League Super Bowl that generated a viewership of 113.7 million people worldwide.²¹ Three hundred of Intel’s Shooting Star sUAS provided a pre-recorded backdrop for a portion of musical artist Lady Gaga’s halftime performance.²² A single pilot (with one additional pilot available as a backup) controlled each of these Intel light shows driven by UAS swarm logic.²³

One recent example of military swarm logic advancement was three US Navy F/A-18 Super Hornets releasing 103 sUAS during a Pentagon Strategic Capabilities Office exercise in October 2016 at China Lake, California.²⁴ The Perdix UAS, developed by the Massachusetts Institute of Technology (MIT), demonstrated "collective decision-making, adaptive formation flying, and self-healing" swarm behaviors during this exercise.²⁵ Interestingly, MIT constructed the Perdix UAS by snapping readily available engines onto 3-D printed frames.²⁶ This meshing of 3-D printing technology and mass drone swarms indicates the threat highlighted in this paper may arrive sooner rather than later. When this threat does arrive, it would be useful to have a defensive system capable of defending military assets from sUAS swarm attacks.



Figure 3: Perdix UAS²⁷

Directed Energy Overview

One of the few technologies capable of defending against UAS swarms is DE. This section will begin with a DE overview before discussing how DE can be brought to bear as a defensive tool against UAS swarms.

There are two types of DE pertinent to military operations: lasers and microwaves. Although lasers and microwaves are both manifestations of electromagnetic energy, they are characterized by different wavelengths and, therefore, different frequencies.²⁸ The relationship between wavelength and frequency is inverse, with wavelength (measured in meters) decreasing from left to right along the electromagnetic spectrum and frequency (measured in hertz) increasing. See Figure 4 for a visual representation of the electromagnetic spectrum.

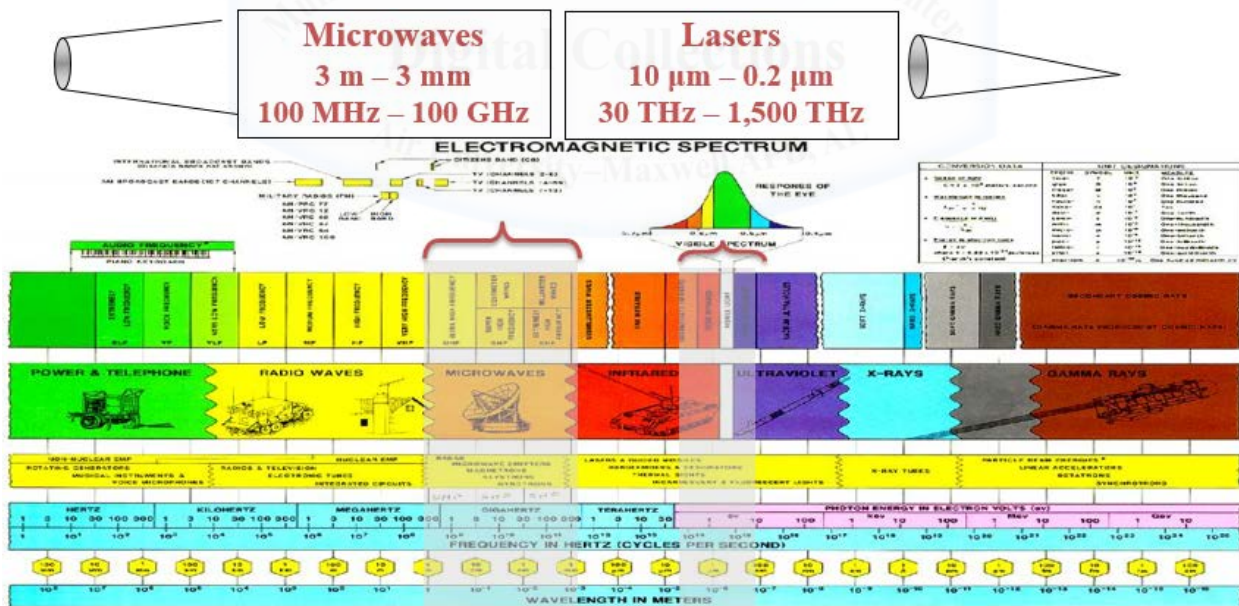


Figure 4: The Electromagnetic Spectrum²⁹

Lasers and microwaves can be further categorized as either continuous wave or pulsed based upon how energy is emitted from their source. Whether a form of DE is continuously beamed or pulsed can fundamentally change the way the energy interacts with targets.

For example, continuous wave lasers (CWL) affect targets by depositing energy, which typically results in a build-up of heat at the point of impact. Depending on the material, this heat buildup can result in burning through material layers until structural/component failure occurs.³⁰ Several types of lasers are capable of producing continuous beams to include chemical lasers like the YAL-1 Airborne Laser (ABL), and electric lasers such as diode-pumped or fiber lasers.

Pulsed lasers affect targets differently. The very high energy of a short pulse tends to cause ablation (stripping away of molecules and atoms) at the point of impact, more than heating.³¹ These molecules can take on very high-energy states, creating plasmas at or near the point of impact, which, with proper timing, can be ignited to produce shock waves.³² Depending on the frequency with which a laser is pulsed, internal electronic effects are also possible.³³ For both continuous wave and pulsed lasers, atmospheric attenuation limits the effective range and aiming precision.³⁴

Continuous wave microwaves, such as the one in your kitchen, also heat. However, microwaves heat by exciting water molecules, and in the right frequency range is useful to heat food.³⁵ The Active Denial continuous wave microwave system is at a much higher frequency than a typical microwave oven, and therefore only penetrates a small distance into the skin, targeting the skin layer's pain receptors.³⁶

In contrast, pulsed microwaves affect targets not by heating, but by creating an electromagnetic field that can induce currents in electrical wires. These currents can upset or destroy electronic components/systems.³⁷ Unlike lasers, atmospheric attenuation, clouds, and moisture do not affect microwaves.³⁸

This paper focuses on CWL and pulsed microwave DE, as their effects are well suited to the sUAS swarm threat. The next section will summarize two fiber CWL systems, one pulsed

high-powered microwave (HPM) system, and one electronic warfare/jamming system that indicate the promise DEW systems provide toward defeating the future sUAS swarm threat.

Current Directed Energy Systems

The demand signal for systems capable of defending against sUAS has spiked in recent years. Defense contractors have utilized both government and internally funded programs to address the supply component of this challenge (or opportunity depending on your point of view). It is clear that ground-based kinetic air defense systems in the US military inventory today are not suitable to address the future sUAS swarm from an economic standpoint. For example, even someone without an economic degree will clearly recognize that shooting down a \$200 small quadcopter UAS with a \$3 million Patriot missile is not a sustainable solution. However, one “very close [US] ally” recently took this action according to a statement by General David Perkins, Commander, US Army Training and Doctrine Command, during the Army's Global Force Symposium in March 2017.³⁹ The following four systems present promising alternatives to counter the future sUAS swarm threat.

High Energy Laser Mobile Test Truck

The High Energy Laser Mobile Test Truck (HELMTT) is a US Army Space and Missile Defense Command/Army Forces Strategic Command (USASMDC/ARSTRAT) asset on an Army Heavy Expanded Mobility Tactical Truck chassis.⁴⁰ The HELMTT is a mobile, modular testbed that provides risk reduction services to US Army laser-based developmental programs.⁴¹ According to Adam Aberle, the HELMTT demonstrator program manager, "The goal of

HELMTT is to integrate new and emerging component technology that supports a high energy laser system, then test and verify performance.”⁴²

The HELMTT currently contains a 10 kW modified commercial solid-state fiber laser, with plans to incorporate a 50-kW class fiber laser in fiscal year 2018.⁴³ According to Richard DeFatta, director of the USASMDC’s Future Warfare Center, the program will receive a 60 kW laser for integration in April 2017 and ultimately hopes to mount a 100 kW laser on the HELMTT.⁴⁴ This statement indicates that the current threat sUAS pose to deployed US military personnel has accelerated the Army’s focus on potential mobile, laser air defense systems.

The HELMTT has provided promising test results versus sUAS to date. During the 2016 Maneuver Fires Integration Experiment (MFI) at Fort Sill, Oklahoma, the HELMTT successfully downed 15 Group 1 sUAS.⁴⁵ See Figure 6 for an example of HELMTT effects on a sUAS. Future testing will demonstrate the effectiveness of HELMTT-based laser weapons against swarms of UAS. The quantity problem proposed by swarms reduces the laser system’s precision from a benefit to a detrimental characteristic. Laser-based systems, like those tested on the HELMTT, must overcome this challenge by either reducing the time required to defeat targets (e.g. increase power at target) or increase the rate at which they can slew from one target to the next.



Figure 5: HELMTT⁴⁶



Figure 6: sUAS downed by HELMTT during MFIX 2016⁴⁷

Mobile Expeditionary High Energy Laser

The Mobile Expeditionary High Energy Laser (MEHEL) and the HELMTT make up the USASMDC/ARSTRAT Warfighter Experimentation with High Energy Lasers (WEHEL) portfolio.⁴⁸ The MEHEL, housed on a Stryker-armored fighting vehicle chassis, is another mobile testbed used to support US Army laser-based developmental programs. Like the HELMTT, the MEHEL's promise is generation of combat ready laser systems that provide the

US military with options to defeat sUAS at a cost of only \$30 per shot (the approximate amount of burned diesel fuel required to power each laser shot).⁴⁹

The original MEHEL system, which shot down 15+ sUAS during MFI 2016, was equipped with a 2 kW solid-state fiber laser.⁵⁰ The current system, MEHEL 2.0, contains a 5 kW laser and numerous counter-UAS (C-UAS) components from the US Army Aviation and Missile Research, Development, and Engineering Center's (AMRDEC) mobile integrated capability efforts to date.⁵¹ AMRDEC developed these mobile integrated capability components under its Counter-UAS Mobile Integrated Capability (CMIC) program. Since Lt Col Palmer highlighted CMIC as "*the most promising system available*" in his paper regarding increased investment in DE systems to defend against sUAS, MEHEL 2.0 likely made great strides toward C-UAS effectiveness over its predecessor (emphasis in original).⁵²

MFI 2016 was not the MEHEL system's last proving ground. In early 2017, MEHEL 2.0 took part in the Joint Improvised-Threat Defeat Organization's (JIDO) UAS Hard-Kill Challenge at White Sands Missile Range, New Mexico.⁵³ Addressing the current threat of sUAS armed with explosives falls under JIDO's mission to facilitate DoD "actions to counter improvised threats with tactical responsiveness and through anticipatory, rapid acquisition in support of Combatant Commands' efforts to prepare for, and adapt to, battlefield surprise in support of counter-terrorism (CT), counter-insurgency (COIN), and other related mission areas, including counter-improvised explosive device (C-IED)."⁵⁴ During the JIDO UAS Hard-Kill Challenge, MEHEL 2.0 proved that its 5 kW laser could defeat Group 1 sUAS and that a single small combat vehicle (with a radar and laser installed) could self-cue, target, and engage these threats.⁵⁵ Like the HELMTT, time will tell whether required power or targeting switching

technology enhancements will allow these laser-based systems to counter the emerging sUAS swarm threat.



Figure 7: MEHEL⁵⁶



Figure 8: sUAS downed by MEHEL during MFIK 2017⁵⁷

Phaser

The Phaser is a pulsed HPM demonstrator system that was developed by Raytheon.⁵⁸ Although it is not vehicle-mounted, the Phaser is moderately transportable since a 20-foot enclosed trailer houses the system and the dish that directs a classified amount of electromagnetic energy.⁵⁹ Since atmospheric attenuation, clouds, and moisture do not affect

microwaves, the Phaser provides an all-weather, deep magazine defense to the future sUAS swarm threat.

In a video approved for public release in October 2016, the Phaser's effects on sUAS at Fort Sill in a September 2013 test are evident.⁶⁰ Relying on inputs from integrated radars, like the MPQ-64 Sentinel or Close Combat Tactical Radar, the Phaser took out multiple Flanker (Group 1) and Tempest (Group 2) sUAS during this test.⁶¹ The PHASER's HPM defeats sUAS by frying their electrical control systems, stopping their motors, and, ultimately, making the targets fall from the sky. Distinct from the aforementioned laser-based HELMTT and MEHEL systems, the PHASER simultaneously defeated multiple sUAS since the band of electromagnetic energy projected from its HPM system is more dispersed than that of laser energy. This characteristic, although beneficial to defeating the future sUAS swarm threat, does increase the need for HPM system collateral damage considerations. Regardless, as stated by Popular Mechanics, the PHASER system's performance to date "makes a fairly convincing case for microwave weapons on the battlefield."⁶²



Figure 9: Raytheon PHASER⁶³

Silent Archer

SRC's Silent Archer C-UAS system takes a different approach to defeating sUAS. Instead of relying on laser or microwave energy to damage hostile sUAS, the silent archer utilizes less destructive electronic warfare techniques to remove the threat. These options include jamming the communication links between a UAS and its operator, providing the UAS a command to return to its originating base, or providing a command for the UAS to execute an emergency landing.⁶⁴ The Silent Archer system has participated in multiple US government exercises since 2005, including MFIIX, the Joint Integrated Air and Missile Defense Organization's Black Dart exercise, the Army Warfighting Assessment, and the Network Integration Evaluation.⁶⁵ Additionally, the Silent Archer has protected major events around the globe, including the 2012 Summer Olympics as well as G8 and G20 summits.⁶⁶

SRC developed the Silent Archer using a system-of-systems approach, wherein they utilized an open system architecture to integrate multiple US Army Programs of Record. For example, the technology readiness level (TRL) 8 LSTAR radar provides 360 degree and 3D detection capability of UAS.⁶⁷ Another proven system utilized in the Silent Archer is the TRL 9 AN/VLQ-12 CREW Duke System, which SRC boasts as the "most widely deployed counter-IED system protecting our warfighters against roadside bombs today."⁶⁸ The CREW Duke system conducts the Silent Archer's software driven electronic warfare techniques that counter sUAS. Although detailed explanation of these techniques is unavailable due to sensitivity, SRC claims that their radio frequency methods allow Silent Archer to defeat both single UAS and swarms.⁶⁹ Other Silent Archer components include an EO/IR camera, a user display/interface system common to US Army forward operators, and an optional direction-finding unit that can help determine the UAS operator's position.⁷⁰

One very appealing characteristic of the Silent Archer is its modularity. The Silent Archer is available in expeditionary (or mobile), fixed-site, or fly away kit configurations.⁷¹ This modularity makes the Silent Archer an attractive solution to defend personnel and equipment on a range of military operating locations. These locations could include everything from a well-established US Air Force fighter aircraft base, to a Navy carrier strike group, to an Army forward operating base, to the clearing in a field chosen by a Marine Recon unit to hunker down for the evening.



Figure 10: SRC Silent Archer Expeditionary Configuration⁷²



Figure 11: SRC Silent Archer Fixed-Site Configuration⁷³



Figure 12: SRC Silent Archer Fly Away Kit⁷⁴

Ideal System Attributes

Although the enhancement of power output levels for laser and microwave systems suited for the battlefield largely remains their greatest barrier to mass production and fielding, it is not too soon for concerned program management professionals in the US military services to consider the attributes of an ideal sUAS swarm defense system. These ideal attributes should include the following: scalable, layered, fused, modular, and open.

The ideal system to defeat sUAS swarms will first be scalable. A scalable DEW is one capable of changing the power output between each shot. Scalable DEWs can answer the following question. How much energy should this shot include to ensure desired effect while limiting collateral damage? US military pilots regularly address this question during dynamic strike operations. For example, MQ-9 Reaper aircraft can be simultaneously loaded with both AGM-114 Hellfire missiles and GBU-12 500-pound laser guided bombs. Although the Joint Terminal Attack Controller seeking Close Air Support may request a 500-pound GBU-12 to

ensure destruction of an unoccupied target vehicle loaded down with weapons, the MQ-9 pilot could recommend using an AGM-114 instead to reduce potential collateral damage since the vehicle is in an active urban environment. DEWs should be able to identify exactly what type of system they are targeting, use known munitions effectiveness tables to determine the effective power on target required, calibrate the weapon to provide the appropriate power output, take the shot, and continue this cycle as they reengage the same target or move on to another.

In order for the ideal DE sUAS swarm defense system to be scalable, associated targeting methodology will require sufficient information regarding expected DE effects versus a range of materials and systems. The Joint Munitions Effectiveness Manual (JMEM) provides expected munition effectiveness information for mission targeteers and weapon systems. The Joint Technical Coordinating Group for Munitions Effectiveness (JTTCG/ME) Program Office has the lead on all US JMEM production efforts but has substantial work remaining on its DE efforts.⁷⁵ Defense Science Board (DSB) Task Force reports from 2001 and 2007 highlighted the need for a better understanding of DEW effects.⁷⁶ The 2007 DSB report recommended “an authoritative single source data base for directed energy effects similar to the munitions effects manual for kinetic weapons.”⁷⁷ Inclusion of a JMEM working group and a session providing updated progress on this effort during the 2015 and 2016 Directed Energy Professional Society Symposia, respectively, indicate that further work remains.⁷⁸ Expected effectiveness information for DE must be incorporated into the JMEM to enable scalable DEW systems and widespread employment of these systems.

The ideal system to defeat sUAS swarms will also be layered. This attribute means the DEW system will have both ground-based and airborne components with which it can engage a target. Options for airborne components include aerostats and UAS. One benefit of including

airborne systems in DEW layering is the geometrical options they provide for probability of kill enhancement. Additionally, collateral damage can be minimized by providing options (ground-based and airborne) to the DEW system as to the origin of every shot. Facilities highly disposed to DEW collateral damage should be hardened, to some degree, at the organization employing the DEW's expense.

A layered employment methodology requires that the ideal system to defeat sUAS swarms be fused. This attribute relates to command and control (C2) functionality and means the ideal DEW system is able to share information with other systems in the battlespace. Otherwise, each DEW component (airborne and ground-based) would act as independent systems instead of a singular, integrated system. Additionally, the system would be unable to incorporate targeting information produced by other systems. A fused DEW C2 system will enable accurate target identification, proper selection of the best component to engage each target, and deconfliction from other security operations. Any US weapon system unable to share information with other systems in the battlespace is destined for a short lifespan. The US military's current shift to multi-domain operations and, specifically, the current US Air Force Chief of Staff's Multi-Domain C2 focus area is evidence of this reality.

Finally, like SRC's Silent Archer, the ideal system to defeat sUAS swarms will also be modular and open. A modular DEW system is capable of employment in various modes (mobile or fixed) and can also be scaled in size/scope to effectively defend different locations. Open DEW systems are developed with an open system architecture that allows less complex/costly integration of additional components (e.g. radars, C2 links) than systems built with a closed system architecture. Modularity and open system architectures will increase the economic feasibility of the ideal DE system to defeat sUAS swarms. These characteristics will allow the

ideal system to support most US military operating locations, meaning developmental costs could be shared amongst the services and all buyers would save on production costs due to economies of scale. Additionally, modularity and openness also support potential inclusion of multiple DE types (both laser and microwave) in one DEW system to protect against various target types. Finally, since all services would be familiar with the basic structure and functionality of the ideal DE system, simple on-the-job training programs would suffice prior to operation of differently configured systems during joint deployments. Other actions are required to ensure effective incorporation of the ideal DEW system to defeat sUAS swarms into military operations.

Recommendations

At this point, two major points should be evident to the reader. First, swarms of sUAS *will threaten* US airbases by the 2025 timeframe. Secondly, DEW systems offer an effective defense to the emerging sUAS swarm threat. Three actions must occur before these laser and/or microwave defensive systems become a normalized component of the US Air Force's CONOPS.

First, DEW effectiveness information must be incorporated into the JMEM if laser and microwave defensive systems will become a normalized segment of the Air Force's base defense structure. The JMEM is the combat weaponeering process' foundation and drives simulation and planning efforts at the operational and strategic levels of war. Until the JMEM includes DEW information, these systems will face difficult normalization with US military personnel and processes. A DEW addendum could be added to the JMEM initially to help smooth the incorporation of these weapons into the combat weaponeering process. However, DEWs will

likely propagate throughout the US services at a high rate; therefore, DE effectiveness information should be directly included into the JMEM to ease the incorporation of these weapons into base defense operations.

Second, DEW collateral damage considerations should be explored and standing guidance developed if laser and microwave defensive systems will become a normalized segment of the Air Force's base defense structure. Without national-level DE collateral damage policies in place, any organization employing DEWs will be vulnerable to resource consuming civil litigation. However, the realization that war sometimes results in collateral damage should remain at the forefront of these discussions and not hinder employment of DEW systems to defend against sUAS swarms. Policy regarding consideration of DE collateral damage to space-based systems is already in place. According to DoD Instruction 3100.11, "DoD laser activities in space, or other DoD laser activities that may direct energy above the horizon, must be conducted in a safe and responsible manner, consistent with national security requirements, in order to manage the associated risks to space systems, those systems' mission effectiveness, and humans in space."⁷⁹ The ideal sUAS swarm defense system's scalable and layered attributes and hardening of facilities highly likely to encounter DE collateral damage ideas previously mentioned are a start to doctrine, organization, training, materiel, leadership and education, personnel, and facilities (DOTMLPF) options towards this end. Although the nature of warfare is quickly approaching a time when DEWs will be commonplace, the US services cannot discount the significant effect these weapons can have on non-combatant life and property.

Lastly, innovative Airmen must develop, test, and evaluate CONOPS for DE employment/C2 if these systems will become a part of the Air Force's base defense structure. Based on the Air Force's current organizational structure, responsibility for DEW system

employment against sUAS swarms should fall under the Security Force as a base defense function. Since the Army will likely gain experience with these systems first, an exchange program, where Air Defense Soldiers spend time in the base defense mission operating DEW systems and Security Force Airmen spend time in the air defense mission, would establish a conduit for knowledge transfer. Participation in such an exchange program by even a minimal number of personnel could significantly help the DoD prepare to defend against the sUAS swarm threat.

A major question of this DEW system CONOPS development effort will be defining when a sUAS swarm becomes a threat. This definition will allow production of rules of engagement for organizations employing defensive DEWs and will enable logic generation for semi-autonomous or autonomous operation of these systems. Acceptance of semi-autonomous DEW system operations will become more likely as sUAS swarm technology advances. Additionally, the ability for US adversaries to include a higher number of UAS in swarms and the advancement of UAS autonomous logic will drive the need for more reactive DEW defensive systems. The more man is in the loop the less reactive any defensive system will be. Therefore, CONOPS for DEW system employment to defend US airbases from sUAS swarms at home and abroad will require levels of autonomy uncomfortable to most US citizens today. Interestingly, much higher levels of autonomous operations have occurred in space than terrestrially for a long time. These operations have resulted in tremendous trust in autonomous spacecraft operations. Yes, autonomous operations do occur in space out of necessity due to the tyranny of distance and lack of continual human presence. Likewise, the threat sUAS swarms pose to US airbases necessitates autonomous DEW defensive system operations.

Conclusion

In a 1939 speech to the Society of Automotive Engineers, then Major General Henry “Hap” Arnold said, “A few extra million dollars in research and experimental work spent today, tomorrow may bring us dividends in security that no amount of money could buy.”⁸⁰ In these words, Arnold vocalized his belief that the US military-industrial complex’s aircraft development and production capabilities required more focus, investment, and advancement in order to address emerging national security needs. The current geo-political landscape indicates the time for robust focus and investment on DEW system advancement is now.

The proliferation of sUAS, miniaturization of sensor technology, and advancement of UAS swarm logic foretell that swarms of sUAS will threaten US airbases by the 2025 timeframe. Currently fielded base defense systems are not well suited to combat this emerging threat. A review of several continuous wave laser, pulsed HPM, and electronic warfare/jamming systems indicate DEWs as the best solution. The ideal DE system to defeat the future sUAS swarm threat will be scalable, layered, fused, modular, and open. In order to ensure DE defensive systems become a normalized component of US Air Force base defense operations, three actions must occur. First, DEW effects should be incorporated into the JMEM. Second, DEW collateral damage considerations should be explored and standing guidance developed. Third, DEW system employment/C2 CONOPS, including the incorporation of semi-autonomous and autonomous logic, should be developed, tested, and evaluated. These recommendations should be acted upon immediately as DEW systems are already being employed to counter individual sUAS and the sUAS swarm threat will soon arrive.

Notes

¹ Leslie F. Hauck and John P. Geis II, "Air Mines: Countering the Drone Threat to Aircraft," *Air and Space Journal*, Vol 31, No 1, Spring 2017, pp. 26-40.

² Headwall Photonics, Inc., Nano-Hyperspec, accessed April 19, 2017, <http://www.headwallphotonics.com/spectral-imaging/hyperspectral/nano-hyperspec>; One example of hyperspectral imaging system integration with a sUAS is the Headwall Photonics Nano-Hyperspec system and UASUSA Tempest application discussed in the Threat Discussion section. The Nano-Hyperspec system (with a 12mm lens) weighs 1.32 pounds and is 3 inches x 3 inches x 5.1 inches. As this paper is submitted for grading, I am awaiting a response to a call I placed to the Headwall Photonics Sales Department requesting the cost of the Nano-Hyperspec system on April 27, 2017. However, the small weight and size of the system indicates integration the vignette used to open this paper is plausible.

³ Hauck and Geis, "Air Mines," 26-40; Thomas S. Palmer and John P. Geis II, "Defeating Small Civilian Unmanned Aerial Systems to Maintain Air Superiority," *Air and Space Power Journal*, Vol 31, No 2, Summer 2017, forthcoming.

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¹³ Nano-Hyperspec Data Sheet, Headwall Photonics, Inc., accessed April 19, 2017, https://cdn2.hubspot.net/hubfs/145999/docs/Nano-Hyperspec_2017.pdf?t=1492800532293.

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